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Quantifying the Bering Strait oceanic fluxes and their impacts on sea-ice and water properties in the Chukchi and Beaufort Seas and western Arctic Ocean for 2013-2014

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LONG-TERM GOALS

The oceanic fluxes of volume, heat, and freshwater through the Bering Strait, the only oceanic input to the Arctic from the Pacific, are critical to the water properties of the Chukchi Sea, act as a trigger of sea-ice melt in the Chukchi, provide a subsurface source of heat to the Arctic in winter (with possible impacts on sea-ice), and are a major component of freshwater input to the Arctic (Figures 1 and 2). Quantification of these fluxes (which all vary significantly seasonally and interannually) is crucial to understanding the physics of the western Arctic, including sea-ice retreat timing and patterns, and possibly sea-ice thickness. Prior data [*Woodgate et al.*, 2012] show a ~ 50% increase in the Bering Strait fluxes from 2001 to 2011 (Figure 2), and indicate that remote-sensed data are insufficient to assess the interannual variability in the throughflow and that year-round *in situ* moorings are currently the only effective way of quantifying the oceanic fluxes of volume, heat and freshwater from the Pacific to the Arctic Ocean.

The long-term goals of this project are:

- to make the necessary observations to quantify the oceanic properties and fluxes of the Pacific inflow to the Arctic on timescales of hours to years;

and to use these observations to:

- understand the causes and consequences of changes in the flow on the subarctic and Arctic system and beyond; and

- provide annually updated estimates of these quantities to the research community and the general public for related regional, arctic, and global studies, e.g., for other ONR-supported Arctic research; for various regional studies of the flow structure and properties of the Chukchi Sea (including providing data relevant to commercial activities in the Arctic); and for model validation and data assimilation in models of the Chukchi and Beaufort Seas and the Arctic Ocean.

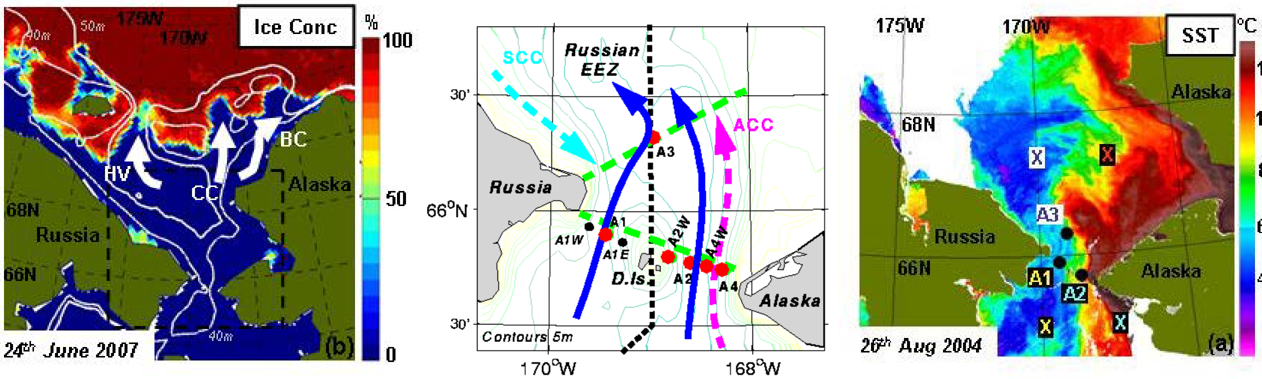

FIGURE 1: (Left) Chukchi Sea ice concentration (AMSR-E) with schematic topography. White arrows mark three main water pathways melting back the ice edge [Woodgate et al., 2010]. (Middle) Schematic of Bering Strait flows marking the annual mean (northward) flow through the two channels of the strait (blue arrows); the northward flowing Alaskan Coastal Current (ACC) found seasonally along the Alaskan Coast (mauve dotted arrow); and the southward flowing Siberian Coastal Current (SSC) present sometimes along the Russian coast (cyan dotted arrow). Also shown are the mooring locations of the 8 mooring "high resolution" array deployed from 2007 to 2013 (black and red dots). Green dotted lines mark typical hydrographic survey lines stretching east-west across the strait and through the northern mooring site. Depth contours are from IBCAO [Jakobsson et al., 2000]. D.Is. marks the Diomede Islands in the center of the strait. (Right) Sea Surface Temperature (SST) MODIS/Aqua level 1 image from 26th August 2004 (courtesy of Ocean Color Data Processing Archive, NASA/Goddard Space Flight Center). White areas indicate clouds. Note the dominance of the warm ACC along the Alaskan Coast, and the suggestion of a cold SCC-like current along the Russian coast [Woodgate et al., 2006]

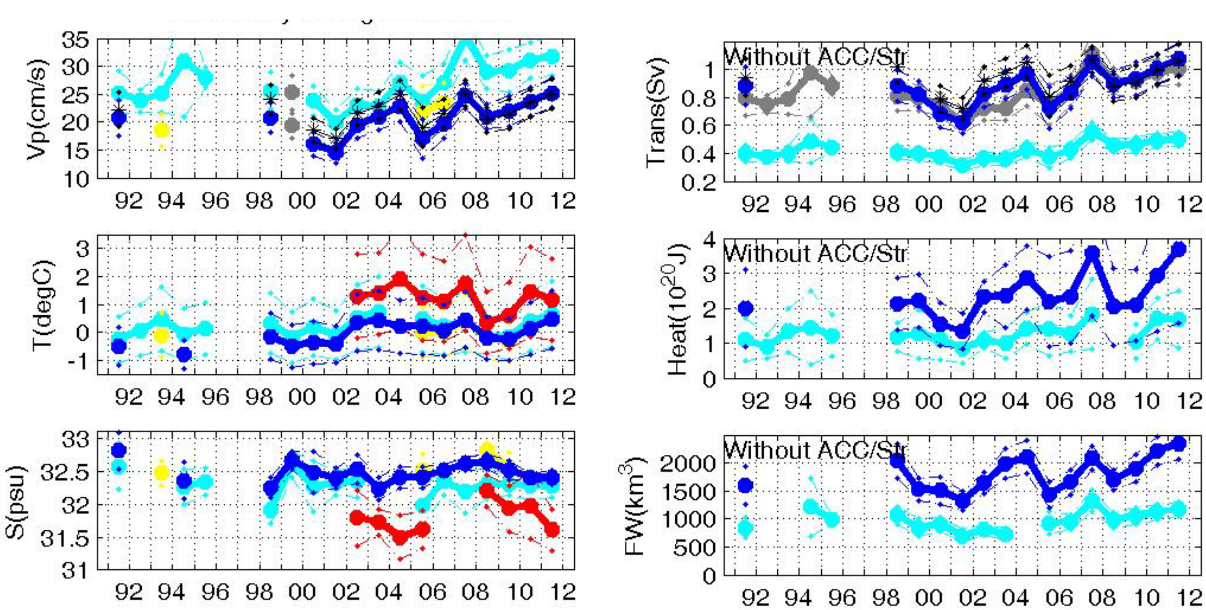

FIGURE 2: Motivation for the current study. Annual means (A1-yellow; A2-cyan; A3-blue; A4-red) of near-bottom principal component (~northward) of velocity (Vp), temperature (T) and salinity (S) (left three panels); and estimates of transport, heat flux and freshwater flux (right three panels).

(Mooring locations are shown in the maps of Figure 1.) For transport and flux estimates, blue (from A3) are for the entire strait and cyan (from A2) are only for the eastern channel. For transport, gray line is the entire strait transport as estimated from A2 only. Black stars mark earlier data corrected for changes in instrument depth. Contributions to the fluxes from stratification and the ACC (both not included) are ~ 1 - 2×10^{20} J/yr (heat) and 800 - 1000km^3/yr (freshwater). Dashed lines indicate estimated errors in the means. Grey dots in Vp indicate results from partial years (used for flux estimates). Updated from Woodgate et al., [2006], see also Woodgate et al., [2012] and Woodgate et al., [2015].

OBJECTIVES

The specific objectives of this project are:

1) to deploy and recover *in situ* moorings and perform hydrographic surveys to quantify water properties and oceanic fluxes of volume, heat, and freshwater through the Bering Strait from summer 2013 to 2014, maintaining a key Arctic oceanographic time-series started in 1990;

2) to quantify recent change in the Bering Strait oceanic fluxes compared to the last decades;

3) to provide *in situ* data and oceanic flux information for validation and assimilation in ocean and ice models of the Bering Strait, Chukchi and Arctic regions.

APPROACH

Since 1990, a sparse array of moorings has been deployed in the Bering Strait region almost continuously. From 2007 to 2013, a set of 8 moorings were deployed in the strait region in a high resolution array (Figure 1) to provide data to design a more modest array of moorings that could be used to quantify the key fluxes and properties of the throughflow.

Data from the high resolution array show that the **flow field is strongly coherent throughout the strait except for the boundary currents**, with the first EOF of along-strait velocity computed for all seven sites in the strait proper explaining over 50% of the flow variance over one year [*Woodgate et al.*, in prep]. The largest cross-strait variability in the flow comes from the seasonally present Alaskan Coastal Current (ACC), which adds ~ 10% to the volume flux. The analysis suggests that the **volume flux can be well estimated by measuring the flow both at the Alaskan Coastal Current site (A4) and at either A3** or the central channel sites (A2 or A1).

Similarly to velocity, most of the temperature and salinity (TS) structure in the strait is related to the warm, fresh, seasonal presence of the ACC [*Coachman et al.*, 1975; *Woodgate and Aagaard*, 2005], with the Siberian Coastal Current (SCC) playing only a minor role [*Weingartner et al.*, 1999; *Woodgate et al.*, 2005a; *Woodgate et al.*, 2015]. In winter, the water column is well mixed. In summer, CTD data indicate a mostly 2-layer system, with the upper layer (10-20m thick) being warmer and fresher [*Woodgate and Aagaard*, 2005; *Woodgate et al.*, 2010]. The extra heat/freshwater in this seasonal upper layer are ~ 20% of the total heat/freshwater fluxes, thus upper layer TS data are vital to realistic estimates of these fluxes [*Woodgate et al.*, 2006]. While satellite Sea Surface Temperatures (SSTs) can be used to infer upper layer temperature, *in situ* measurements are still required for upper layer salinity. Overall however, given the lower layer (30-50m thick) is thicker than the seasonal upper layer, the volumetric bulk of the water properties of the throughflow are set by the properties of the lower layer. In this lower layer (outside the ACC), there is a modest east-to-west decrease in temperature (<0.5ºC) and increase in salinity (<1psu) across the strait, likely relating to ACC waters being mixed into the rest of the strait. However, these across-strait differences are small compared to the seasonal change (-1.8 to 2.3°C, and ~ 31.9 to 33 psu [*Woodgate et al.*, 2005b; *Woodgate et al.*, 2015]). With the motivation of using a reduced number of moorings to quantify water properties and fluxes, it has been hypothesized that **site A3 (in US waters) gives a useful average of the water properties through the strait** [*Woodgate et al.*, 2006; *Woodgate et al.*, 2007]. Given the logistical challenges of working in Russian waters and the lack of measurements there during most of the 1990s, it is also of interest to assess to what extent data from US waters can quantify the contribution of the Russian channel to the throughflow.

As discussed above, the high coherence of flow in the strait suggests the total transport can be inferred from two measures – the mean flow quantified at any mid-strait site and the ACC, likely quantified from A4. **Data indicate that A3 TS can be used to predict the TS of the Russian channel (A1) generally to ~0.1ºC and 0.2psu** (Figure 3). Those uncertainties result in ambiguity in the heat and freshwater transports of ~$0.1\text{x}10^{20}$J/yr and 150km^3/yr, which are much less than the estimated interannual variability (Figure 2).

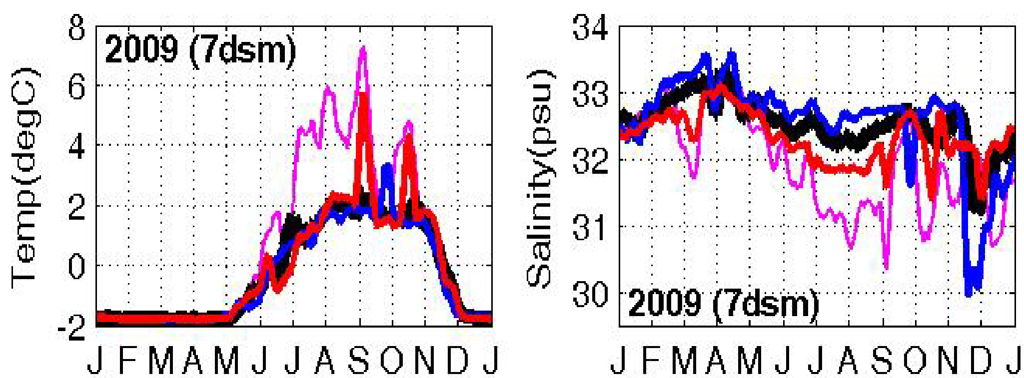

FIGURE 3: Seven-day smoothed (7dms) time-series of lower water column temperature (left) and salinity (right) from the Russian channel (A1, blue), the US channel (A2, red), the ACC (A4, magenta) and the climate site (A3, black) for 2009.

This suggests that measurements from US waters, including measures of stratification (in TS and velocity) and the ACC, can provide enough information for reasonable estimates for the full strait physical fluxes of volume, heat and freshwater. Furthermore, A3 TS are obviously a combination of A1 and A2 TS, indicating that A3 and A2 data combined may estimate Russian channel water properties.

Thus, this project is for a year-long (summer 2013-summer 2014) deployment of moorings at these three established core sites, viz.: **the center of the eastern channel (A2), the Alaskan Coastal Current (A4) and at the "climate" site at the north (A3)** (Figure 4). Funding of these moorings prevented a break in the 23 year long time-series.

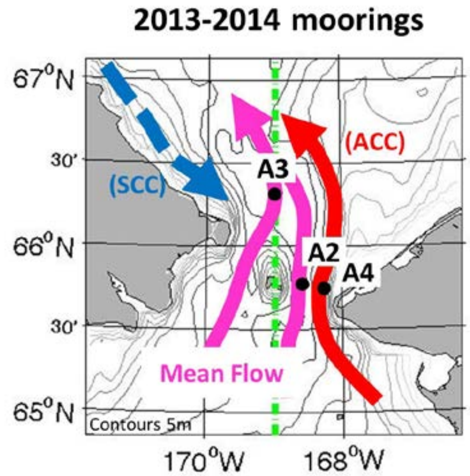

FIGURE 4: The 3 mooring locations (A2, A3, and A4) in the Bering Strait deployed for this proposal. Colored arrows are schematic for the mean flows and coastal currents (ACC=Alaskan Coastal Current; SCC=Siberian Coastal Current). Depth contours are from IBCAO [Jakobsson et al., 2000]. Green dashed line at 168º 58.7'W indicates the US and Russian border. All the moorings lie in US waters.

This work is led by PI, Rebecca Woodgate, who has maintained moorings in the Bering Strait region since 2000 (building on the then 1 decade long existing timeseries) (see cruise reports at http://psc.apl.washington.edu/BeringStrait.html), and has peer-reviewed publications on interannual change in the region [*Woodgate et al.*, 2006; *Woodgate et al.*, 2012], including impacts of the throughflow on sea-ice [*Woodgate et al.*, 2010], the role of the Pacific inflow in the Arctic freshwater budget [*Woodgate and Aagaard*, 2005], and has provided climatologies for past and on-going Arctic modeling studies [*Woodgate et al.*, 2005b; *Clement-Kinney et al.*, 2014; *Nguyen et al.*, 2016].

WORK COMPLETED

In July 2013, the 3 moorings were successfully deployed from the US research vessel Norseman II, and accompanying CTD sections (Figure 5) were run to give a framework for the moorings and a measure of the hydrography of the southern Chukchi Sea. This work was in collaboration with a concluding NSF AON (Arctic Observing Network) project, which recovered the last year of the high resolution array on the same cruise. Full details of the deployment cruise (July 2013) are given in the cruise report [*Woodgate and BeringStrait2013ScienceTeam*, 2013], available at our website *http://psc.apl.washington.edu/BeringStrait.html* .

In July 2014, a second cruise on the Norseman II recovered the moorings, and ran accompanying CTD sections (Figure 6). (The same cruise also deployed 3 moorings at the same sites, funded by a new NSF-AON grant, Woodgate and Heimbach) Data recovery on the ONR moorings was extremely good., with the ADCPs and lower level temperature and salinity sensors all returning complete records. All 3 moorings also carried upper layer iscat systems, measuring temperature and salinity in the upper water column in depths prone to ice keel damage and logging that data to deeper safer depth. Two of the upper instrument packages (A2 and A4) were missing on recovery, with data showing loss of the upper instrument package in late March and mid May respectively, likely due to sea-ice keels. The upper instrument package on A3 was still present on recovery, and returned a full year of data.

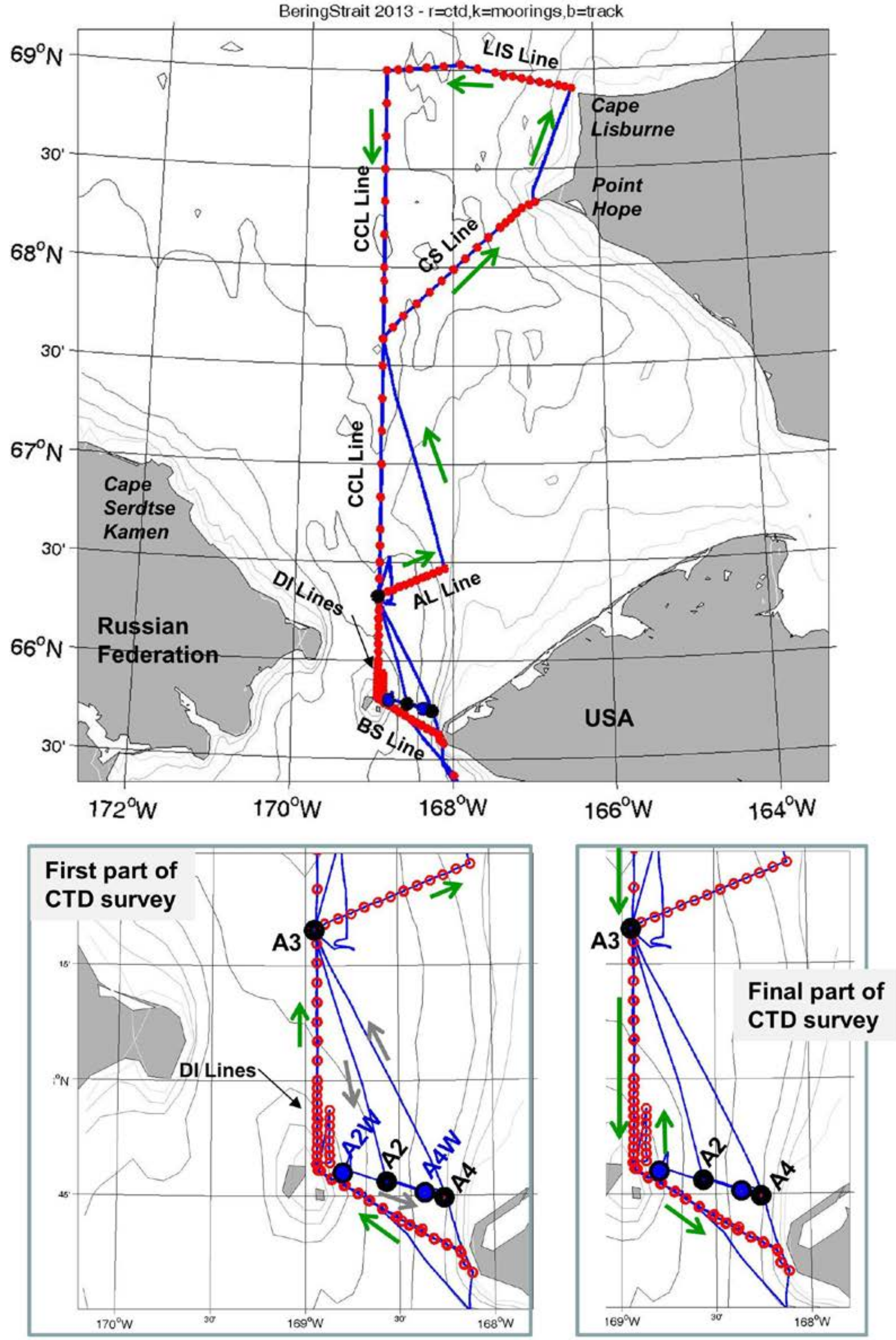

FIGURE 5: Bering Strait 2013 mooring cruise map: Ship-track, blue. Mooring sites, black. CTD stations, red. Grey and green arrows indicate direction of travel (grey during mooring operations, green during CTD operations). Depth contours every 10m from the International Bathymetric Chart of the Arctic Ocean (IBCAO) [Jakobsson et al., 2000]. Lower panels mooring detail: - black solid=recovered and redeployed; black with blue center =recovered, not redeployed.

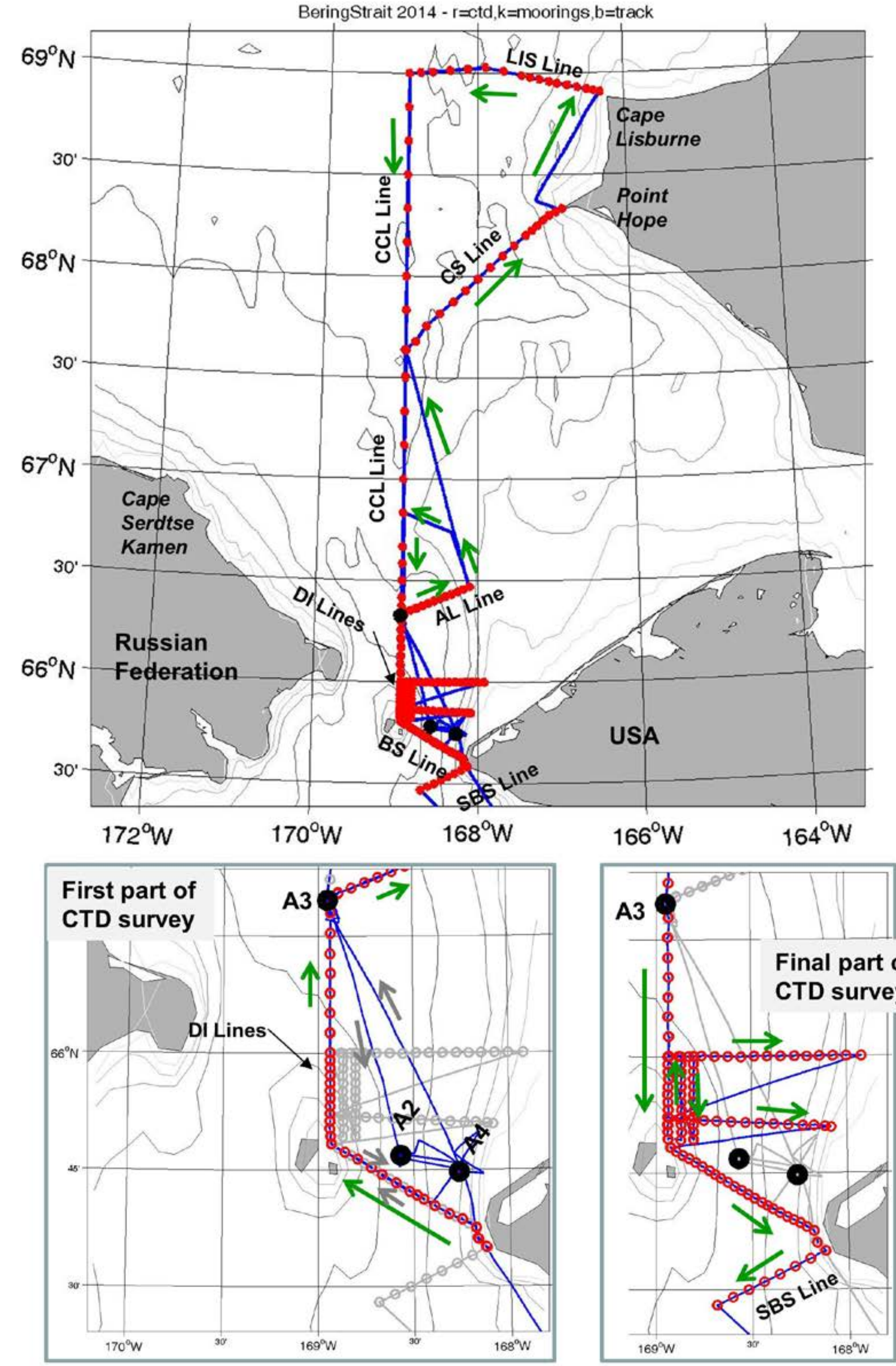

FIGURE 6: Bering Strait 2014 mooring Cruise map. Ship-track, blue. Mooring sites, black. CTD stations, red. Grey and green arrows indicate direction of travel (grey during mooring operations, green during CTD operations). Depth contours every 10m from the International Bathymetric Chart of the Arctic Ocean (IBCAO) [Jakobsson et al., 2000]. Lower panels give detail of strait region at the start (left) and end (right) of the cruise.

RESULTS

These 2013-2014 ONR mooring data allow us to quantify oceanic fluxes between the Pacific and the Arctic from 1990 to 2014. Figure 7 shows the time-series of annual mean velocity, temperature and salinity, and estimates of volume, heat and freshwater fluxes [*Woodgate*, 2015; *Woodgate et al.*, 2015]. Our prior paper [*Woodgate et al.*, 2012] reported on increases in transports of volume, heat and freshwater from 2001 to 2011. The more recent data collected by this ONR grant indicate that, **despite a lower transport in 2012, the Bering Strait throughflow has increased in 2013 and 2014 to ~ 1.2 Sv, significantly greater than the 1990s climatology** of ~ 0.8 Sv. In contrast to previous results which suggested this was previously 1/3rd due to local wind forcing [*Woodgate et al.*, 2012], we find **changes in the local wind is now driving only ~ 20% of this flow increase** (even though wind can explain ~ 50% of the hourly variability in the flow) [*Woodgate*, 2015]. **Freshwater fluxes** (relative to 34.8psu) **are also at a record maximum in 2014, viz. > 3500km^3/yr, a significant increase over the 1990s climatology** of ~ 2500km^3/yr. This is a **~ 40% increase** in freshwater flux since 2001, and is mostly (90%) due to increased flow, although there is also a freshening of waters coming through the strait. Similarly, **heat fluxes are also high in 2014**, around 5x10^{20}J/yr (relative to the freezing temperature, -1.9degC), comparable to the previous record heat flux in 2007. **This is sufficient heat to melt ~2x10^{6}km^2 of 1m thick ice**.

These are vital data for understanding and modeling causes and impacts of these recent changes in the Strait on both the physical and the interdisciplinary systems of the Chukchi and Arctic.

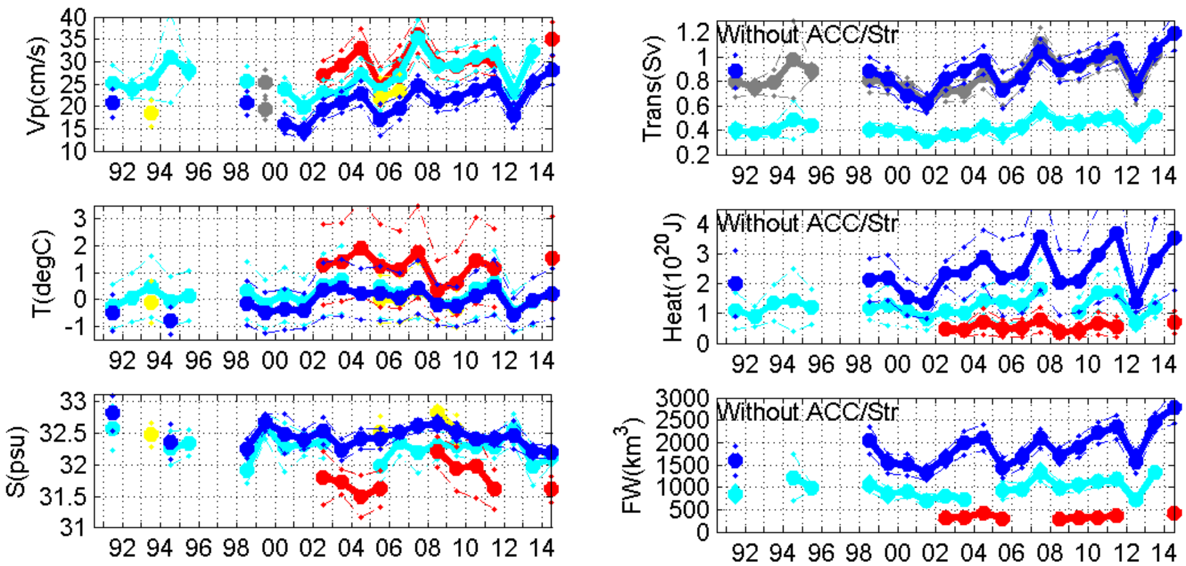

FIGURE 7: Bering Strait Annual means (A1-yellow; A2-cyan; A3-blue; A4-red) of near-bottom principal component (~northward) of velocity (Vp), temperature (T) and salinity (S) (left three panels); and estimates of transport, heat flux and freshwater flux (right three panels). For transport and flux estimates, blue (from A3) are for the entire strait and cyan (from A2) are only for the eastern channel. For transport, gray line is the entire strait transport as estimated from A2 only. Note that contributions to the fluxes from stratification and the ACC (both not included) are ~ 1 - 2×10^{20} J/yr (heat) and 800 - 1000km^3/yr (freshwater). Dashed lines indicate estimated errors in the means. Grey dots in Vp indicate results from partial years (used for flux estimates). Updated from [Woodgate et al., 2006] and [Woodgate et al., 2015].

IMPACT/APPLICATIONS

By providing an improved evaluation of the Bering Strait fluxes, this project contributes to local, Arctic and global studies. Most topically, with the startling retreat of the Arctic sea-ice, quantifying the heat flux and water properties through the Bering Strait and the impacts of the Bering Strait throughflow on Arctic ice and stratification become urgent issues in the quest to understand causes of Arctic sea-ice retreat. Within regional oceanography, the work provides vital information for physical, and other studies within the Bering Strait and Chukchi Sea, since the physical oceanography of the Chukchi Sea is dominated by the properties of the Bering Strait throughflow. Thus our work also has impacts for recent commercialization (e.g., transit, and oil and gas exploration) in the Chukchi Sea and western Arctic. Since the Bering Strait is fed from the south, the Bering Strait throughflow is also some indicator of conditions on the Bering Sea shelf, an economically important zone for U.S. fisheries. The Bering Strait throughflow is also the Pacific input to the Arctic Ocean, and is important for maintaining the halocline in roughly half of the Arctic Ocean [*Woodgate*, 2013]. The Pacific inflow also brings heat into the Arctic. The fate of Pacific waters in the Arctic relates to their density which is, to a large extent, set by the time the waters traverse the Bering Strait [*Woodgate et al.*, 2005a]. Globally, the Bering Strait throughflow is an important part of the global freshwater budget. Models suggest that an increase in the Bering Strait freshwater flux may weaken the Atlantic meridional overturning circulation [e.g., *Wadley and Bigg*, 2002]. Other modeling studies count the Bering Strait flow as critical for the stability of world climate [*De Boer and Nof*, 2004; *Hu and Meehl*, 2005; *Hu et al.*, 2007].

Thus, a better observational estimate of the Bering Strait flow and its variability is critical for a wide range of studies. The products from this project – year-round measurements of the Pacific inflow to the Arctic - continue a 23 year time-series of a critical ocean connection at a time of dramatic change. The data products are being used for a wide variety of modeling and observational research studies (including model validation, and data assimilation).

RELATED PROJECTS

Related projects include the on-going ONR-DRI efforts in the Arctic, and the international Arctic Observing Network. Bering Strait mooring data are permanentaly archived at the National Oceanographic Data Center (now called National Centers for Environmental Information) and are also made freely available on our website, http://psc.apl.washington.edu/BeringStrait.html.
Voluntary registration at our data site shows the data is in demand for work ranging from climate modeling to King Crab fishing, including a wide variety of studies covering local, Arctic and global subjects (North Pacific, Gulf of Alaska, Bering Sea, Chukchi Sea, Arctic Ocean, Arctic Ocean outflows, North Atlantic). In addition, our data are actively being used for a variety of projects, including heat studies (M.Sereeze), acoustic studies (M.Guerra and K.Stafford), interpreting marine mammal acoustic observations from the strait (E.Escajeda and K.Stafford), bowhead studies (B.Ferriz), pink salmon studies (J.Gann) and zoo- and icthyoplankton studies (L.Eisner).

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Talks:

Woodgate, R.A., et al., Bering Strait – Feb 2013 update, invited talk for Distributed Biological Observatory meeting in Seattle, Feb/March 2013

Woodgate, R.A., 2013, Physical drivers of the western Arctic seas, invited talk and committee member for planning meeting called by the Executive Office of the President, Office of Science and Technology, on Developing a Conceptual Model of the Arctic Marine Ecosystem, April 30 – May 2, 2013, Washington DC.

Woodgate, R.A., 2013, The Frozen Ocean, invited talk at Women's International Shipping and Trade Association (WISTA), Seattle, May 2013

Woodgate, R.A., 2013, Puzzles of the Western Arctic Seas, invited speaker at Gordon Research Conference on Coastal Oceanography at the University of New England, Biddeford, north of Boston, USA, June 2013

Woodgate, R.A., et al, 2013, What's new in the Bering Strait, invited presentation for ASOF steering committee meeting in Helsinki, November 2013 (in absentia)

Woodgate, R.A., 2013, A Physical Oceanographer's view of the Bering Strait, invited presentation for Bering Strait Currents workshop, Kawarek, Nome, Alaska, November 2014.

Woodgate, R.A., 2014, Changing Oceanography of the Bering Strait, invited evening presentation at UAF Northwest Campus in Nome, 27th June 2014

Woodgate, R.A., 2014, Bering Strait – the Pacific Gateway to the Arctic, talk for ONR site review, Washington DC, Oct 2014.

Woodgate, R.A., 2015, 25 years (1990-2015) of year-round measurements in the Bering Strait - what do we know, and what do we still not know? Accepted talk at AON (Arctic Observing Network) meeting, Seattle, USA, 17th-19th Nov, 2015.

Woodgate, R.A., 2016, Bering Strait - the Pacific Gateway to the Arctic. 25 years (1990-2015) of year-round measurements in the Bering Strait - what do we know and what do we still NOT know?, invited contribution to IARPC Chukchi/Beaufort Team Meeting, Spring 2016.

Woodgate, R.A., 2016, Bering Strait - the Pacific Gateway to the Arctic. 25 years (1990-2015) of year-round measurements in the Bering Strait - what do we know and what do we still NOT know?, invited contribution to the ASOF meeting in Lerici, Italy, Spring 2016.

Outreach:

Woodgate, R.A., and J.Johnson, 2013, Ocean Watchdogs – how to measure the ocean when you are not there, mooring exhibit at the Polar Science Weekend, at Seattle's Pacific Science Center, 28th Feb-3rd March , 2013.

Woodgate, R.A., and J.Johnson, 2014, Ocean Watchdogs – how to measure the ocean when you are not there, mooring exhibit at the Polar Science Weekend, at Seattle's Pacific Science Center, 7-9th March, 2014.

Woodgate, R.A., 2014, Changing Oceanography of the Bering Strait, invited evening presentation at UAF Northwest Campus in Nome, 27th June 2014

Woodgate, R.A., and J.Johnson, 2015, Ocean Watchdogs – how to measure the ocean when you are not there, mooring exhibit at the Polar Science Weekend, at Seattle's Pacific Science Center, 27th - 20th February, 2015.

Woodgate, R.A., and J.Johnson, 2016, Ocean Watchdogs – how to measure the ocean when you are not there, mooring exhibit at the Polar Science Weekend, at Seattle's Pacific Science Center,4th 6th March, 2016.

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14. ABSTRACT
The oceanic fluxes of volume, heat, and freshwater through the Bering Strait, the only oceanic connection between the Arctic and the Pacific, are critical to the water properties of the Chukchi Sea, act as a trigger of western Arctic sea-ice melt, provide a subsurface source of heat to the Arctic in winter, and are ~ $1/3^{rd}$ of freshwater input to the Arctic. Quantification of these fluxes (which all vary significantly seasonally and interannually) is essential to understanding and predicting recent dramatic changes in the western Arctic, including sea-ice retreat timing and patterns, and sea-ice thickness. Prior data show a ~ 50% increase in the Bering Strait fluxes from 2001 to 2011, and indicate that year-round *in situ* moorings are currently the only effective way of quantifying Pacific-Arctic oceanic exchange.
This project supported three year-round moorings measuring Bering Strait fluxes from 2013 to 2014, (preventing a break in the 23-year long Bering Strait time-series). Results show recent fluxes to be significantly higher than 1990s climatologies, with the 2014 volume flux almost double the 2001 flux, driving record freshwater fluxes in 2014, and the 2014 heat flux, enough heat to melt ~$2x10^6 km^2$ of 1m thick ice, comparable to the 2007 record high.

15. SUBJECT TERMS
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